IBIS

Preliminary Report

Analysis of the Economics of
DC Arc CVD Diamond

Contract Number: N00014-93-C2044

IBIS Associates, Inc.
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1st Quarterly Report 1993

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Executive Summary

From the research conducted to date, it appears that the cost today to produce 1,000 six inch wafers, 1 mm thick, by the DC arc deposition technology is $4,072/wafer. Of the six operations included in this analysis (substrate preparation, deposition, etching, polishing, metallizing, and inspection), the deposition step contributes the bulk of the cost (85%). The total cost of a finished substrate is dominated by the cost of equipment (30.6%) and materials (25%). High equipment costs are attributable to the low deposition rate, and to the high capital investment for deposition equipment. High material costs are attributed to the lack of gas recycling and to the use of expensive high purity gases.

Preliminary results indicate that recycling of gases could reduce gas costs substantially, but the equipment to accomplish this task must cost less than $200,000 under existing conditions to be economically justifiable. Today, a best estimate is that a gas recycling system would add $275,000 to the capital equipment cost of a deposition station. In future phases of this project, IBIS Associates will continue to investigate the conditions under which gas recycling will be warranted.

Preliminary analyses indicate the close dependence of material costs on gas purity. Statistical analysis suggests that as the purity of gases increases towards 100%, the gas price increases towards infinity. This relationship implies that it is imperative to identify the lowest acceptable gas purity for use in deposition.

Description of DC Arc Process

The six steps analyzed in this report for the fabrication of diamond film are Surface Preparation, Deposition, Etching, Lapping, Metallization, and Inspection (see Figure 1). The context applied to each unit operation is briefly explained below.

Surface Preparation

The first step in the manufacture of diamond films is to prepare the surface of the substrate on which the diamond will be grown. In its final use as an electronic substrate, the performance of diamond films depends, in part, on surface finish, and the surface should be as smooth as possible. The smoothness of the lower side of the diamond film is determined by the smoothness of the substrate on which it is deposited. To minimize polishing of the diamond, it is advantageous to polish the softer substrate instead.

Silicon, tungsten, and molybdenum are the most commonly used substrates for growing diamond. A database of disks of various diameters and thicknesses made from these materials is included in the model. For the baseline analysis, it is assumed that deposition is on a silicon disk.

Flowchart for DC Arc Diamond Deposition

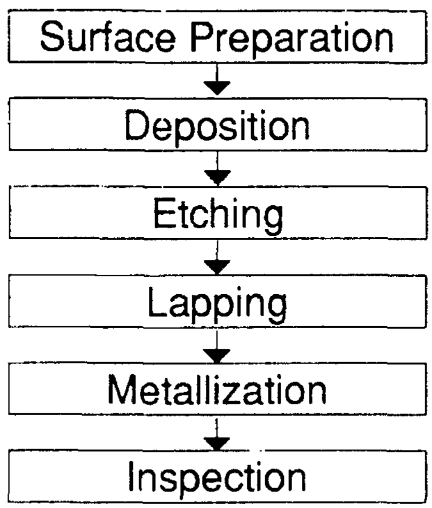

Figure 1

Deposition

The second step, deposition, involves the formation of the diamond film. The diamond growing substrate is mounted on a water cooled fixture perpendicular to the axis of the DC Arc nozzle, inside a chamber at a controlled pressure. The nozzle is made of an anode and a cathode, one surrounding the other, between which flows a controlled mix of gases. The voltage is set so as to create an arc discharge through the flowing gas, thus creating a gas plasma. The carbon containing gas is introduced downstream of the arc. The substrate is positioned at the end of the plasma stream and a diamond film forms on this substrate.

Etching

The third step in the baseline process, as modeled, is etching to remove the silicon substrate. The substrate/diamond wafers are placed in a fifty wafer cassette, then placed in a 5:1:1 bath of water, hydrofluoric acid, and nitric acid, designed to completely etch away the substrate. After the etching has been completed, the cassette is placed in a rinse bath. The entire process must be performed under a hood in order to draw away noxious gases. Disposal costs associated with waste liquids range from four to eight dollars per liter.

Substrate etching is only applicable when the substrate is not reusable, as in the case of silicon. For other materials, the substrate is mechanically separated from the diamond film and reconditioned for reuse.

Lapping

The fourth step is the lapping of the diamond film. This step can either be a one sided or two sided process. (In other instances, depending on the end use application, lapping may be unnecessary.) In the lapping operation, diamond wafers are placed in carriers or holders, and lapped by the abrasive action of diamond grit. Diamond wafers (typically three to five per batch), are held in place by the holders and travel in an elliptical pattern on the surface of a rotating, "O" shaped plate. During this process, a diamond grit slurry flows through grooves in the plate, lapping the surface of the diamond films. The size of the grit chosen depends on the initial and desired surface roughness.

Other techniques for lapping or polishing have been reviewed in the technical literature, including chemical and ablative techniques for surface reduction. However, according to most experts surveyed, conventional abrasive lapping remains the technology of choice.

Metallization

The fifth operation is the metallization of the clean, lapped, diamond film surface. The technology analyzed to date has been limited to DC vacuum sputtering. The wafers are placed in a carousel, then loaded into the metallization, or sputtering equipment. There are usually two or more chambers; one as an air lock, in which vacuum is drawn, and the rest for sputtering. In the sputtering chambers, there is an anode and a cathode, between which the diamond film passes; the cathode material coats the diamond film. A variety of sputtering targets are in the sputtering chamber, resulting in the successive coating of metal layers. In the baseline analysis, it was assumed that three metal layers are applied, consisting of titanium, platinum and gold.

Inspection

The last step is the inspection of the finished diamond films. At this time, the extent and nature of the inspection activities are not known. At minimum, it is assumed that quality checks for dimensional accuracy and structural integrity will be required. Additional tests may monitor thermal conductivity, purity, grain size, etc.

Baseline Costs

IBIS Associates, through its use of Technical Cost Modeling (TCM), has created a predictive, spreadsheet based model of the DC Arc diamond film technology. Sections of this model are still undergoing active investigation and modification. This section presents both the input assumptions and the cost estimates for each unit operation, as they are currently modeled. Key input data were obtained primarily through discussions with industry personnel. Selected summaries from representative discussions are presented in Appendix A and B.

Moving forward, IBIS anticipates refining the input assumptions, developing predictive correlation equations for inputs such as equipment costs, and initiating detailed verification of the model's inputs and outputs.

In the analyses presented in the upcoming sections, it was assumed that each operation involved the use of "dedicated equipment" (i.e. the equipment is not being used for other manufacturing jobs). Additionally, standard default values were applied for equipment downtimes, rejection rates, number of laborers per operation and building space requirements. IBIS will continue to investigate values for these factors. However, recognizing that there are no commercial scale production facilities for making diamond films, establishing definitive values for these parameters will not be possible. Instead, IBIS will rely on experience gained from modeling other, similar manufacturing processes.

The baseline case study, defined in Table 1, is assumed to be a six inch diamond wafer, one millimeter thick, produced at an annual volume of one thousand pieces.

DC Arc Economics: Product Specifications

PRODUCT SPECIFICATIONS		
Part Name	6 in. substrate	NAME
Wafer Diameter	15.24 cm	WAFER
Coating Thickness	1,000 um	THIK
Annual Production Volume	1 (000/yr)	NUM
Length of Production Run	5 yrs	PLIFE

Table 1

Surface Preparation

Surface Preparation Inputs

The substrate is assumed to be a six inch diameter, silicon wafer, 0.15 inch thick (3810 um) and costing $43 each. These substrates are polished five at a time for one hour, to create a mirror quality finish. The 0.15 inch wafer thickness is typical for the DC Arc process. The lot size of five wafers per batch is representative of a small scale substrate polishing machine. One such machine can easily supply 1,000 substrates per year.

The model assumes that the same type of polishing equipment is used for polishing silicon and the diamond wafers. Capital costs for equipment are predicted based on a statistical relationship derived from the analysis of collected industry data.

Table 2 presents the key input assumptions used to determine surface preparation costs.

DC Arc Economics: Surface Preparation Inputs

PROCESS RELATED FACTORS - SURFACE PREPARATION

Process In Use?	1	[1=Y 0=N]	USE1
Dedicated Investment	1	[1=Y 0=N]	DED1
Process Rejection Rate	5.0%		REJ1
Average Equipment Downtime	20.0%		DOWN1
Direct Laborers Per Station	1		NLAB1
Substrate Material	11	[menu #]	MATL1
Pieces Per Batch	5	pcs/batch	PCS1
Process Time	1	hr	PTIME1
Building Space Requirement	150	sqft/sta	FLR1

Table 2

Surface Preparation Cost Estimates

A summary of the estimated surface preparation costs is presented in Table 3. As shown, the largest element of cost is the silicon wafer material, accounting for $52.23 or 54.5% of the total. As mentioned, silicon wafers of the chosen geometry are priced at $43.00 each. The difference between $52.23 and $43.00 is attributable to the method in which scrap losses are accounted. Because each step in the process involves some losses or rejects, 1,202 silicon wafers must be prepared in order to produce 1,000 good diamond wafers. The cost of all 1,202 wafers is distributed on to the 1.000 good wafers ultimately produced.

Overhead labor costs are the second most significant cost at 26.1% of the total cost of the operation.

The model permits the selection of alternative substra.e materials. For example, the use of molybdenum presents the interesting tradeoff between higher substrate costs and material reusability. A detailed tradeoff analysis is presented in the section on sensitivity analyses, later in this report.

DC Arc Economics: Surface Preparation Cost Estimates

DC ARC CVD TCM: SURFACE PREPARATION
IBIS ASSOCIATES, INC. Copyright (c) 199[illegible] v4.[illegible]

	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$52.23	$52,229	54.5%	
Direct Labor Cost	$5.41	$5,409	5.6%	
Utility Cost	$0.10	$102	0.1%	
FIXED COST ELEMENTS				
Equipment Cost	$5.23	$5,233	5.5%	$26,166
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.75	$750	0.8%	$15,000
Maintenance Cost	$3.29	$3,293	3.4%	
Overhead Labor Cost	$25.00	$25,000	26.1%	
Cost of Capital	$3.86	$3,863	4.0%	
TOTAL FABRICATION COST	$95.88	$95,880	100.0%	$41,166

Table 3

Deposition

Deposition Inputs

Table 4 presents the key input assumptions used in estimating the costs of the deposition step. The inputs involve equipment assumptions, gas concentrations, flow rates, recycling rates, and the diamond mass deposition rate.

Based on information gathered from early commercial production activities, all gases used in this model are assumed to be "five nines pure," meaning 99.999% pure. The concentrations of these gases are chosen as follows: 24% hydrogen, 1% methane, and 75% argon, based on publications (1,2,3,4) for the DC Arc technology. Additionally,

DC Arc Economics: Deposition Inputs

PROCESS RELATED FACTORS - DEPOSITION

Process In use?	1 [1=Y 0=N]		USE2
Dedicated Investment	1 [1=Y 0=N]		DED2
Process Rejection Rate	1.0%		REJ2
Average Equipment Downtime	10.0%		DOWN2
Direct Laborers Per Station	0.25		NLAB2
Load/Unload Laborers	1 /sta		LLAB2

	Menu #	vol%	
Hydrogen	3	24.0%	GASA VOLA
Carbon Containing Gas	5	1.0%	GASB VOLB
Carrier Gas	14	75.0%	GASC VOLC
Other Gas	0	0.0%	GASD VOLD
		100.0%	

Hydrogen Recycle Rate	0.0%	RECYC
Carrier Gas Recycle Rate	0.0%	RECYC2
Gas Recycle Equipment Cost	$275,000 /sta	MCH2A
Deposition Rate	2 g/hr	DEP2
Carbon Capture Factor	20.0%	CCF2
Machine Load/Unload Time	120 min/cyc	PTIME2
Available Deposition Time	8,640 hrs/yr	DAYHR2
Machine Cost	$600,000 /sta	MCH2B
Machine Power	90.0 kW	POW2
Cooling Water	50.0 GPM	WATER2
Building Space Requirement	1,000 sqft/sta	FLR2

Table 4

the recycle rates are chosen as 0% for hydrogen and 0% for argon, reflecting the existing state of DC Arc technology.

Within the model, there is an option to specify separate levels of argon and hydrogen recycle. Invoking this option causes an additional capital expense to be incurred. For instance, if argon recycling is chosen, the equipment cost is increased by $275,000 per deposition station. The additional capital expenditure provides for equipment that adsorbs carbon based gases, converts residual hydrogen to water, dries the gas mixture to remove water, and recirculates the recovered argon. IBIS will continue to investigate alternative technologies for recovering and purifying gas streams, including identifying centralized gas recovery options for supporting multiple deposition stations.

For the baseline analysis, the deposition rate has been assumed to be 2 gram/hr, with a carbon capture factor of twenty percent. While much higher deposition rates have been demonstrated with the DC Arc process, it is likely that performance and quality constraints will preclude extremely rapid deposition rates for the production of electronic substrate grade diamond films. A more complete investigation of deposition rate is being undertaken.

Another critical input assumption for the deposition step is that the capital equipment will cost $600,000 per station. It is anticipated that future versions of the model will have a correlation equation for the calculation of equipment costs based on process parameters such as the deposition rate and power.

Deposition Cost Estimates

As shown in Table 5, the largest cost driver in the deposition step is the equipment cost, accounting for 31.3% of the total cost of the operation. High equipment costs per wafer can be attributed to two factors: 1) high capital investment costs for each deposition machine, and 2) low deposition rate or process throughput, which leads to the need for multiple deposition stations. Unless one or both of these factors can be changed, DC Arc based diamond film will remain relatively expensive.

Also significant is the material cost (25%), caused by the high gas flow rates and gas prices. Using the cost model, several scenarios were investigated involving both the use of low cost, low purity gases, as well as the implementation of gas recycling. As the models evolve, further investigation of gas cost minimization strategies will be explored.

Utility costs account for 10.6% of the total, suggesting an important cost reducing business strategy. In the baseline analysis, the price of electricity was assumed to be $0.10/kWh. In various regions of the world, electric energy is available for as low as $0.010/kWh, which would result in a significant cost savings for each wafer.

DC Arc Economics: Deposition Cost Estimates

DC ARC CVD TCM: DEPOSITION
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$862.36	$862,362	25.0%	
Direct Labor Cost	$229.81	$229,814	6.7%	
Utility Cost	$364.59	$364,590	10.6%	
FIXED COST ELEMENTS				
Equipment Cost	$1,080.00	$1,080,000	31.3%	$5,400,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$30.00	$30,000	0.9%	$600,000
Maintenance Cost	$480.00	$480,000	13.9%	
Overhead Labor Cost	$37.50	$37,500	1.1%	
Cost of Capital	$369.29	$369,286	10.7%	
TOTAL FABRICATION COST	$3,453.55	$3,453,552	100.0%	$6,000,000

Table 5

Etching

Etching Inputs

Table 6 presents the inputs to the etching process. Etching rates are tabulated in the Material Database, and is assumed to be 20 um/min for silicon. The rinse time of thirty minutes, capacity of fifty wafers, machine cost of $6,000 per station, and etchant cost of $100 per liter are based on information collected from industry sources. These values, as well as the associated cost estimate, will be verified over the course of this program.

Etching Cost Estimates

As shown in Table 7, the most significant cost element for the etching step is found to be the overhead labor cost, which, in turn, is based on assumptions of an average salary of $50,000/yr for indirect labor and a number of indirect laborers associated with the operation. Materials costs are found to be the second largest cost element, attributable to the high etchant price and disposal fees.

The etching cost analysis will continue to be reviewed and refined. However, unless these reviews reveal that the assumptions in the baseline analysis are radically incorrect, not much attention will be focused on this operation. With an estimated total operation cost of $39.83 per wafer, this step is almost two orders of magnitude less expensive than the deposition step. Consequently, it does not warrant a great deal of attention.

DC Arc Economics: Etching Inputs

PROCESS RELATED FACTORS - ETCHING			
Process In Use?	1	[1=Y 0=N]	USE3
Dedicated Investment	1	[1=Y 0=N]	DED3
Process Rejection Rate	1.0%		REJ3
Average Equipment Downtime	10.0%		DOWN3
Direct Laborers Per Station	1		NLAB3
Load/Unload and Rinse Time	30	min/batch	PTIME3
Pieces Per Batch	50		PCS3
Machine Cost	$6,000	/sta	MCH3
Etchant Cost (incl Disposal)	$100	/liter	ETCH3
Machine Power	0	kW	POW3
Building Space Requirement	100	sqft/sta	FLR3

Table 6

DC Arc Economics: Etching Cost Estimates

DC ARC CVD TCM: ETCHING
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$7.60	$7,600	19.1%	
Direct Labor Cost	$1.66	$1,662	4.2%	
Utility Cost	$0.00	$0	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$1.80	$1,800	4.5%	$9,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.50	$500	1.3%	$10,000
Maintenance Cost	$1.52	$1,520	3.8%	
Overhead Labor Cost	$25.00	$25,000	62.8%	
Cost of Capital	$1.75	$1,751	4.4%	
TOTAL FABRICATION COST	$39.83	$39,833	100.0%	$19,000

Table 7

Lapping

Lapping Inputs

The inputs for the lapping operation, shown in Table 8, involve the type of lapping operation and the scale of the machine. The number of sides lapped and the number of lapping steps are dependent on the end-use application.

For the baseline analysis, electronic heat sinks, it is necessary to lap only one side of the wafer. (The other side is already smooth and flat because it was assumed to be deposited on the polished surface of a silicon substrate.) The side being lapped contains both microscopic roughness attributable to the growth of diamond crystals, as well as a macroscopic "out of flatness" or crowning, due to unequal growth rates across the face of the wafer. The flatness and surface finish required to fabricate a heat sink can be accomplished using a two step lapping process, lapping off an assumed volume of 4.5 cubic centimeters, or twenty percent of the original volume.

In the baseline analysis, it is assumed that there are five pieces per station, and the lapping rate is assumed to be 0.017 cc per minute. The lapping rate is a critical input assumption, and efforts are underway to corroborate the rate currently assumed. The lapping machine uses a diamond grit slurry priced at $53 per liter, with a flow rate

DC Arc Economics: Lapping Inputs

PROCESS RELATED FACTORS - LAPPING			
Process In Use?	1	[1=Y 0=N]	USE4
Dedicated Investment	1	[1=Y 0=N]	DED4
Process Rejection Rate	5.0%		REJ4
Average Equipment Downtime	15.0%		DOWN4
Direct Laborers Per Station	1		NLAB4
No of Sides Lapped	1	(1 or 2)	SIDE4
No of Lapping Steps	2		LAPS4
Volume of Material Lapped	4.5	cc	TLAP4
Pieces Per Batch	5		PCS4
Load/Unload and Clean Wafers	40	min	PTIME4
Average Lapping Rate	0.017	cc/min	RATE4
Lapping Slurry Cost	$53	/liter	LAP$4
Lapping Slurry Usage Rate	0.5	liter/hr	LAPR4
Lapping Plate Life	320	hrs	PLAL4
Building Space Requirement	400	sqft/sta	FLR4

Table 8

through the system of 0.5 liter/hour. The lapping plate life for lapping diamond film is estimated at 320 hours.

Lapping Cost Estimates

The key cost driver for this process is the diamond lapping grit, accounting for 50.9% of the total process cost, as shown in Table 9. This is followed by the labor cost at 26.1% of the process cost. The high labor costs can be attributed to the long process time, which depends on the lapping rate.

DC Arc Economics: Lapping Cost Estimates

DC ARC CVD TCM: LAPPING
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$95.40	$95,400	50.9%	
Direct Labor Cost	$48.98	$48,983	26.1%	
Utility Cost	$0.98	$978	0.5%	
FIXED COST ELEMENTS				
Equipment Cost	$3.58	$3,582	1.9%	$17,909
Tooling Cost	$2.44	$2,445	1.3%	$869
Building Cost	$2.00	$2,000	1.1%	$40,000
Maintenance Cost	$4.63	$4,633	2.5%	
Overhead Labor Cost	$25.00	$25,000	13.3%	
Cost of Capital	$4.32	$4,318	2.3%	
TOTAL FABRICATION COST	$187.34	$187,338	100.0%	$58,778

Table 9

Metallizing

Metallizing Inputs

The inputs for metallization are shown in Table 10. The model allows for three different layers of material. IBIS has ascertained, through industry interviews, that the metallization for a heat sink is a three-metal layer consisting of titanium, platinum, and gold. The thicknesses are all assumed to be 0.1 um, or just enough to create a metal layer. A machine capable of accomplishing this task costs $500,000.

Metallizing Cost Estimates

As shown in Table 11, significant cost drivers for the metallization operation are all related to the cost of the equipment. These include the investment in the equipment (58.1%), its maintenance (23.6%), and the cost of capital (16.6%).

Because the analysis assumes dedicated equipment, the entire capital investment for metallization is distributed onto the electronic substrates being modeled. At 1,000 wafers per year, the metalization station is idle 98% of the time. Given this

DC Arc Economics: Metallization Inputs

PROCESS RELATED FACTORS - METALLIZATION

Process In Use?	1	[1=Y 0=N]	USE5
Dedicated Investment	1	[1=Y 0=N]	DED5
Process Rejection Rate	1.0%		REJ5
Average Equipment Downtime	20.0%		DOWN5
Direct Laborers Per Station	0.1		NLAB5
Load/Unload Laborers	1		LLAB5

	Menu #		Thick (um)	
First Metal Layer	1	Titanium	0.10	MET5A/THK5A
Second Metal Layer	2	Platinum	0.10	MET5B/THK5B
Third Metal Layer	3	Gold	0.10	MET5C/THK5C

Load Time	15	min/cyc	PTIME5
Target Preheat Time	1	min/kW	HTIME5
Pieces Per Batch	6	pcs/batch	PCS5
Machine Cost	$500,000	/sta	MCH5
Metallization Magnetron Power	3	kW	POW5
Building Space Requirement	100	sqft/sta	FLR5

Table 10

inefficiency, it is most probable that any production facility making only 1,000 wafers per year would outsource metallization. At higher production volumes, it could become economical to purchase the metallization equipment described in the model.

DC Arc Economics: Metallization Cost Estimates

DC ARC CVD TCM: METALLIZATION
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$1.28	$1,277	0.5%	
Direct Labor Cost	$0.11	$115	0.0%	
Utility Cost	$0.02	$15	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$150.00	$150,000	58.1%	$750,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.50	$500	0.2%	$10,000
Maintenance Cost	$60.80	$60,800	23.6%	
Overhead Labor Cost	$2.50	$2,500	1.0%	
Cost of Capital	$42.96	$42,963	16.6%	
TOTAL FABRICATION COST	$258.17	$258,170	100.0%	$760,000

Table 11

Inspection

Inspection Inputs

The inputs in Table 12 are the inspection time (5 minutes), the percent inspection (100%), and the cost per inspection machine ($20,000). Because the operation is still under investigation, these numbers are, at best, crude estimates. Future versions of the model will have a detailed breakdown of the inspection steps along with relevant assumptions for each inspection step.

Inspection Cost Estimates

Table 13 show the current breakdown of costs for the inspection operation. Due to the low inspection time, the largest cost is the overhead labor, at 66.6% of the total operation cost. It should be noted that these are preliminary estimates and that the costs estimated for this step are likely to change significantly following a more detailed analysis.

DC Arc Economics: Inspection Inputs

PROCESS RELATED FACTORS - INSPECTION		
Process In Use?	1 [1=Y 0=N]	USE6
Dedicated Investment	1 [1=Y 0=N]	DED6
Process Rejection Rate	5.0%	REJ6
Average Equipment Downtime	20.0%	DOWN6
Direct Laborers Per Station	1	NLAB6
Average Inspection Time	5 min	PTIME6
Percent Inspection	100%	INSP6
Machine Cost	$20,000 /sta	MCH6
Machine Power	0 kW	POW6
Building Space Requirement	0 sqft/sta	FLR6

Table 12

DC Arc Economics: Inspection Cost Estimates

DC ARC CVD TCM: INSPECTION
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$1.97	$1,974	5.3%	
Utility Cost	$0.00	$0	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$6.00	$6,000	16.0%	$30,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.00	$0	0.0%	$0
Maintenance Cost	$2.40	$2,400	6.4%	
Overhead Labor Cost	$25.00	$25,000	66.6%	
Cost of Capital	$2.14	$2,140	5.7%	
TOTAL FABRICATION COST	$37.51	$37,514	100.0%	$30,000

Table 13

Cost Summary

As shown in Table 14, equipment costs are the largest cost element for the DC Arc deposition of diamond. High equipment costs per wafer are attributable to the high capital investment cost for many of the operations, especially the deposition step, as well as the low throughput associated with some of the operations, again, notably deposition. In addition, because the analysis assumes dedicated equipment, and because production volumes are low, underutilized capital investments such as the metallizing equipment add significantly to the cost of equipment on a per wafer basis.

Material costs, which account for 25% of the total, are mainly attributable to the cost of the gases consumed in the deposition step. Material costs can be decreased through the use of less pure gases, or through the implementation of gas recycling.

Table 15 shows the breakdown for equipment and materials, illustrating the percent cost for each operation.

DC Arc Economics: Cost Summary

DC ARC CVD ICM: COST SUMMARY
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$1,018.87	$1,018,868	25.0%	
Direct Labor Cost	$287.96	$287,957	7.1%	
Utility Cost	$365.69	$365,685	9.0%	
FIXED COST ELEMENTS				
Equipment Cost	$1,246.61	$1,246,615	30.6%	$6,233,075
Tooling Cost	$2.44	$2,445	0.1%	$869
Building Cost	$33.75	$33,750	0.8%	$675,000
Maintenance Cost	$552.65	$552,646	13.6%	
Overhead Labor Cost	$140.00	$140,000	3.4%	
Cost of Capital	$424.32	$424,320	10.4%	
TOTAL FABRICATION COST	$4,072.29	$4,072,286	100.0%	$6,908,944

Table 14

DC Arc Economics: Equipment and Material Cost

Operation	Equipment	Percent	Mat'l	Percent
SURFACE PREPARATION	$5	0.4%	$52	5.1%
DEPOSITION	$1,080	86.6%	$862	84.6%
ETCHING	$2	0.1%	$8	0.7%
LAPPING	$4	0.3%	$95	9.4%
METALLIZATION	$150	12.0%	$1	0.1%
INSPECTION	$6	0.5%	$0	0.0%
Total	$1,247	100.0%	$1,019	100.0%

Table 15

Sensitivity Analyses

One of the advantages of a Technical Cost Model is that it permits the flexibility of performing sensitivity analyses. Using sensitivity analyses it is possible to explore the cost implications of changing key input variables such as production volume, gas price, substrate size, etc. As an R&D management tool, these analyses help set development goals for cost effective manufacturing. Further, they help in long term planning, by indicating the cost savings that may be realized through scale-up. Presented in the following sections are the following analyses:

- Cost vs Substrate Life
- Cost vs Gas Price
- Cost vs Recycle Equipment Cost
- Cost vs Lapping Time
- Cost vs Deposition Rate

Cost vs Substrate Life

Substrates are either disposable, as with the baseline scenario for silicon, or they may be reused, as has been suggested for molybdenum. Five different molybdenum substrate thicknesses, each with an assumed number of reuse lives, were analyzed and compared with silicon. The results are shown in Figure 2.

Given the current high cost of the deposition step, the cost of diamond wafers was found to be relatively insensitive to changes in the life of the deposition substrate. At one use, molybdenum substrates are more expensive ($3,497 per finished diamond wafer) than the silicon ($3,465), but the cost of the wafers decreases as the life of the substrate increases. At 46 cycles, the molybdenum-produced wafer costs $3,345, saving $120 per wafer.

For this analysis, the silicon substrate is assumed to be twice as thick as the molybdenum disk in order to have equivalent heat transfer characteristics. Additionally, it is assumed that the maximum life of the molybdenum substrate is determined by its thickness. Starting with a minimum thickness of 254 microns (0.01 inches), the analysis assumes that substrate polishing for each reuse removes 50 microns (0.002 inches) of material.

The cost savings associated with reusable substrates comes from two sources. First, there is a cost savings from spreading the price of the substrate over multiple pieces. Second, reusing the substrate eliminates the need for etching, with its associated capital, labor, material and waste disposal costs. The spent etching liquids are classified as toxic wastes, and disposing of them is a significant expense.

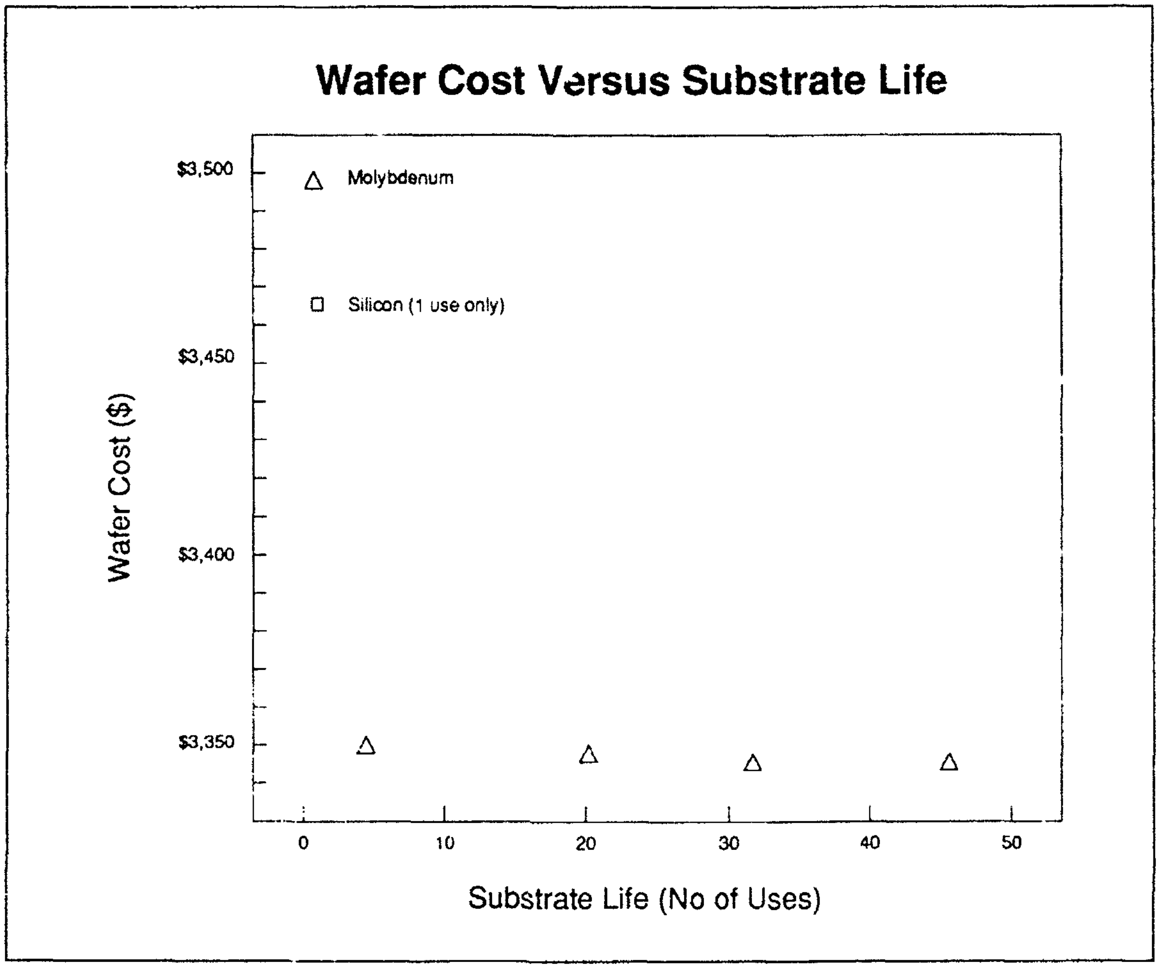
Wafer Cost Versus Substrate Life
Molybdenum
Silicon (1 use only)
$3,500
$3,450
$3,400
$3,350
Wafer Cost ($)
0
10
20
30
40
50
Substrate Life (No of Uses)

Figure 2

Cost vs Gas Price

Figure 3 presents the linear dependencies of part cost on gas prices. The gas price which affects the part cost most significantly is the Argon, because it constitutes 75% of the gas mix. Hydrogen and methane have less influence on cost.

The baseline price of each gas is also indicated in Figure 3. For both argon and hydrogen, the price applies to "five-nines" purity (99.999%). The methane is "four-nines" pure (99.99%). In all instances, it was assumed that the gas was contained in standard cylinders.

The price of industrial gases is strongly dependent on the purity of the gas. Figure 4 shows the price of Argon over a range of purity, from 99.997% to 99.9999% pure. As the purity rises beyond the 99.999% level, the price per standard cubic meter increases

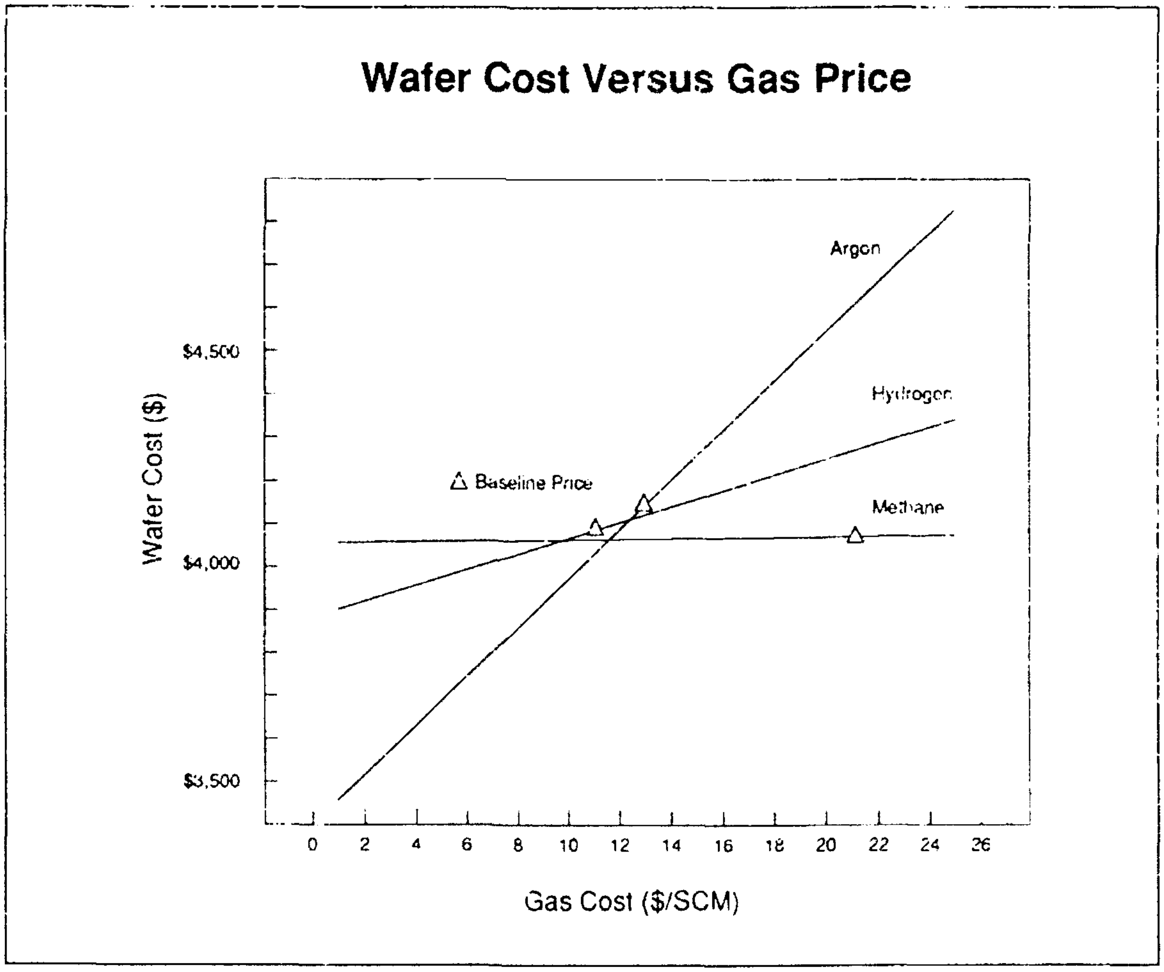

Figure 3

dramatically. A statistical analysis of gas price data reveals that the following equation fits these data well:

Argon Price ($/SCM) = 0.004056*(P/(1-P))^0.7,

where P is the purity of the gas expressed as a fraction (i.e. 99% is .99).

Similar analyses were performed on the prices of hydrogen and methane. The equations derived for predicting these price data are:

Hydrogen Price ($/SCM) = 3.88E-7*(P/(1-P))^1.5,

Methane Price ($/SCM) = 0.489*(P/(1-P))^0.7,

The equations for argon, hydrogen and methane price were all derived from small data sets, and might change significantly if a larger number of data sources were employed.

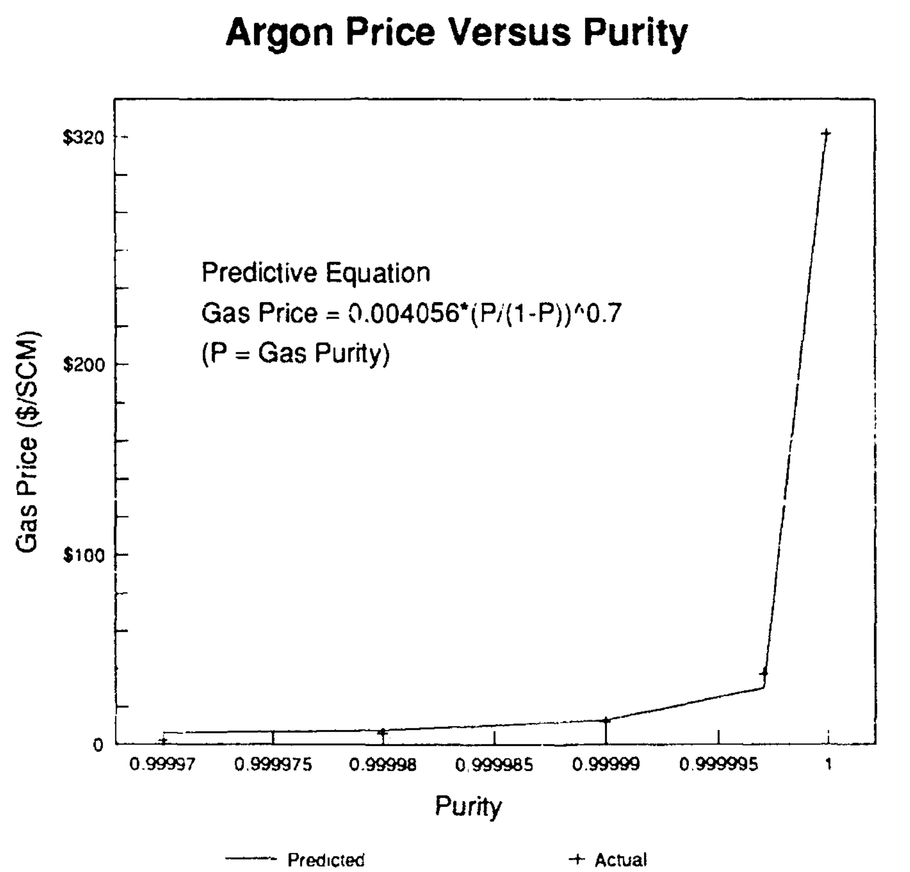

Figure 4

Gas prices are also volume dependent; gases purchased in bulk are significantly less expensive than gas purchased in cylinders. Additionally, gas prices are subject to fluctuations with time. For these reasons, these equations should not be used to price gases, but rather should serve as an indication of the economic incentive for using less pure gas sources.

Today, 99.999% pure argon is priced at $33.09/SCM in cylinders. From the above equation, the estimated price of 99.99% pure argon is $2.56/SCM. If this substitution could be made with no other changes to the process, the savings would be $525 per wafer, or a 13% cost reduction.

Cost vs Recycling Equipment Cost

Today, the capital cost of implementing argon recycling is estimated to be $275,000 per deposition station. However, IBIS anticipates that less expensive gas recycling systems will be identified as this research program progresses. Figure 5 shows the sensitivity of wafer costs to changes in the capital cost of recycling equipment at various levels of argon recovery.

The baseline scenario involves no recycling and no added equipment costs. Consequently, at 0% recycle there is no sensitivity to changes in equipment costs. When recycling is assumed, the cost of each wafer produced depends, in part, on the added cost of the recycling equipment.

For a given level of gas recovery, the maximum justifiable recycling equipment cost is defined by the intersection of the line for that recovery rate with the 0% recycle line.

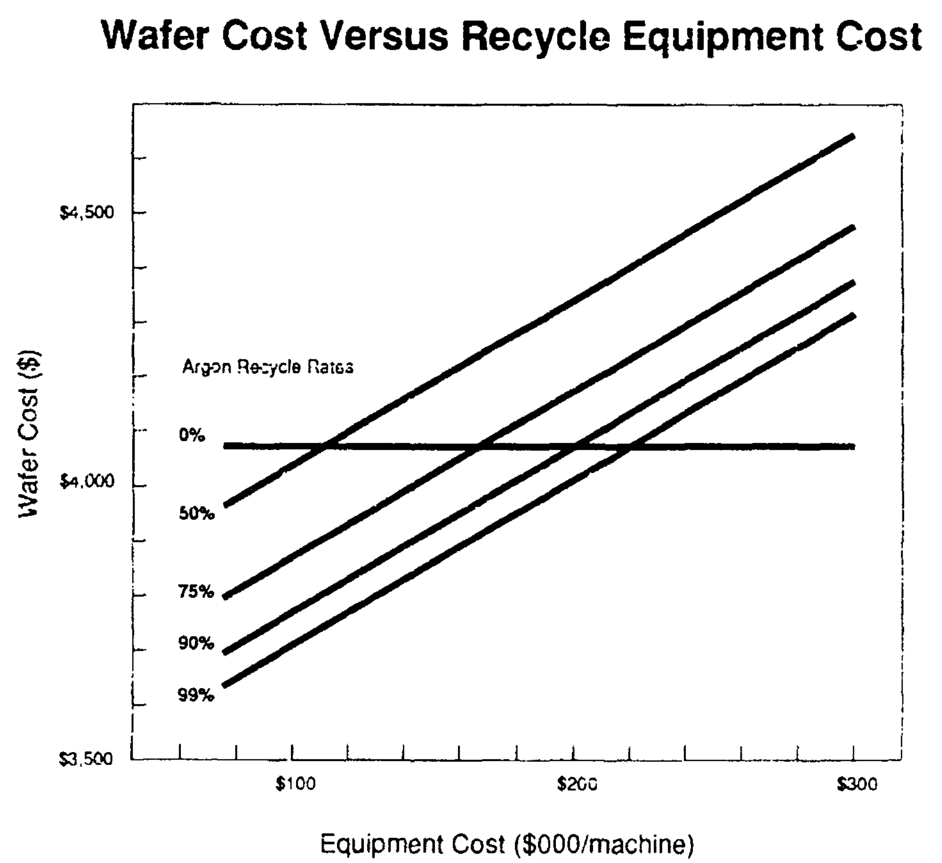

Figure 5

For instance, recycle equipment running at rates of 50%, 75%, 90%, and 99% must cost lower than $115K, $162K, $200K, and $220K, respectively, to be cost effective.

The cost effectiveness of gas recycling depends, in a non-obvious way, on other process parameters within the manufacturing process. For instance, as the deposition rate increases, the breakeven cost of recycling equipment also increases. At 6 grams per hour, the current estimated equipment cost of $275,000 is economically justifiable for 99% argon recovery.

Cost vs Lapping Time

A clear, linear relationship is shown in Figure 6 between wafer cost and lapping time. The steep slope of this line, and the magnitude its effect on wafer costs, indicate the critical nature of the lapping rate assumption. Relatively little information has been collected to date regarding diamond film lapping. IBIS will continue to investigate this operation.

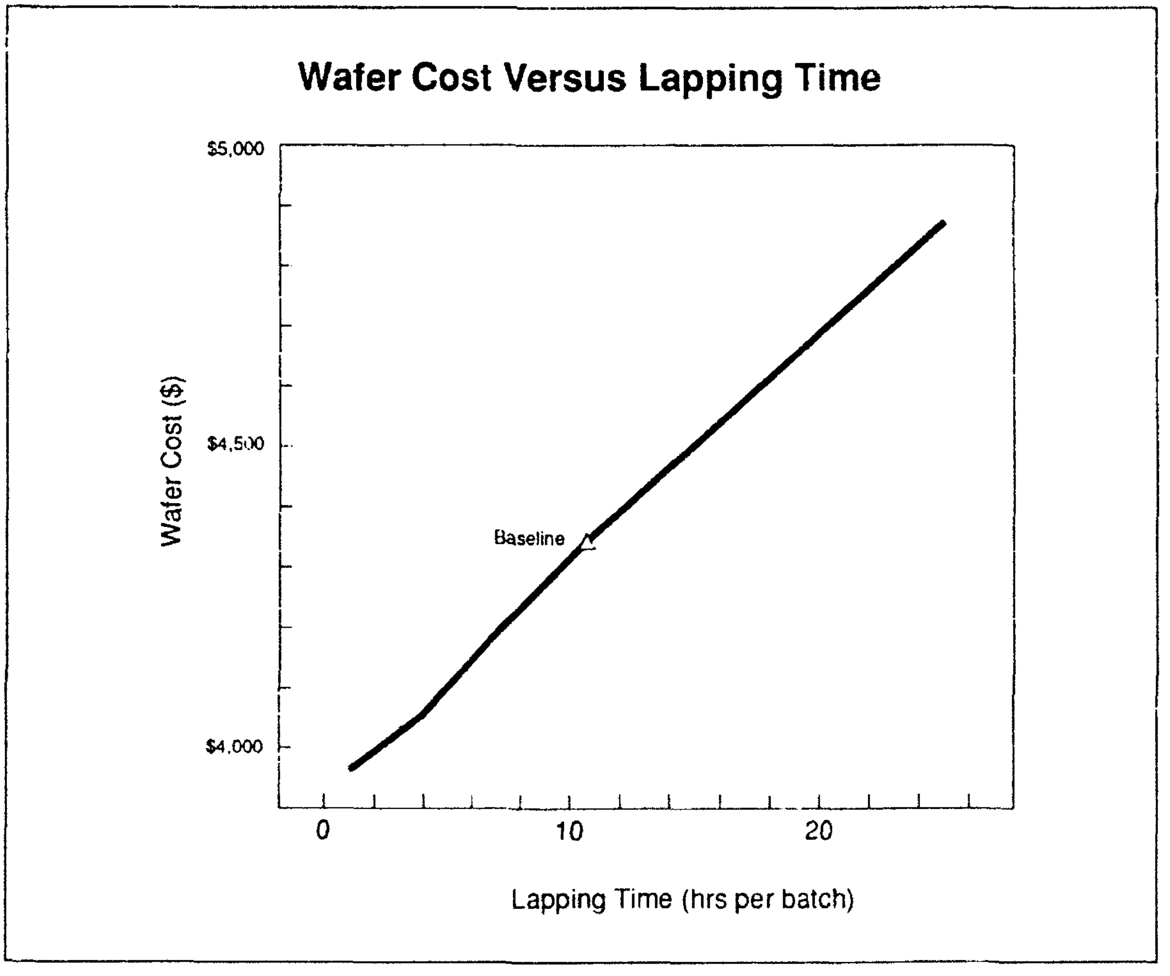

Figure 6

Cost vs Deposition Rate

Figure 7 indicates, all else held constant, the savings realized through increasing the deposition rate. At 2 grams per hour, the cost per wafer is $4,072. Tripling this rate to 6 grams per hour reduces the cost to $2,385 per wafer. Because capital related costs account for the largest fraction of total cost, and because the deposition step dominates the cost of all other steps, increasing the deposition rate has a dramatic influence on the cost per wafer.

Also, the carbon capture factor (CCF), or percentage of carbon atoms which are deposited as diamond, greatly affects the cost of the final diamond film. For instance, an increase in the CCF from five to ten percent results in a $1,800 reduction in cost per part. Increasing CCF decreases the amount of gas consumed in producing a wafer. Deposition systems that require high purity gases and do not incorporate gas recycling should focus on maximizing carbon capture factor.

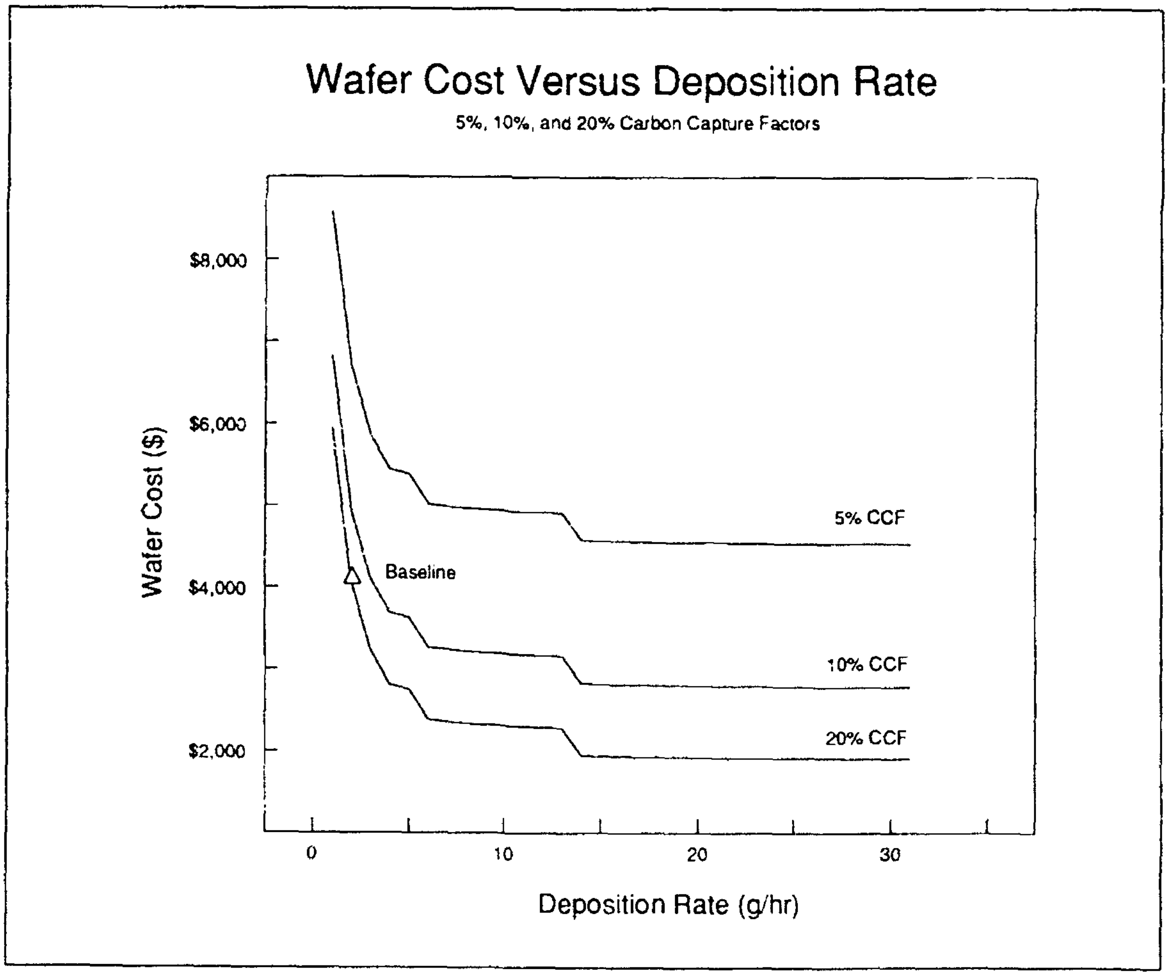

Figure 7

Summary & Conclusions

The cost today to produce 1,000, six inch, polished and metallized diamond wafers, 1 mm thick, by the DC Arc deposition technology is estimated to be $4,072/wafer. The majority of this cost (85%) is attributable to the deposition step, which is capital intensive and slow. The deposition step also involves the consumption of large volumes or relatively expensive process gases.

Three key areas for process cost reduction are:

Deposition Rate - If the deposition rate can be increased by a factor of three, all else held constant, the cost of a finished wafer should be reduced to $2,385.

Gas Recycle - Implementing an argon recovery system is economically justifiable given today's process economics, assuming that the capital cost of this system is less than $275,000 per deposition station.

Gas Price/Purity - Gas prices appear to be inversely proportional to their purity. In today's DC Arc process, relatively expensive "five-nines" pure gases are used. If the purity of these gases can be reduced to "four-nines" purity without adversely effecting the diamond produced, this change would result in a 13% cost reduction from the baseline scenario.

In addition to the three parameters identified above, three process steps require further investigation. These are:

Polishing - The cost of polishing diamond films depends strongly on the time required to perform this operation. To date, relatively little information has been compiled regarding this parameter.

Metallizing - The capital cost of metallization equipment for coating electron wafers is relatively high ($500,000 per station). At current levels of diamond wafer production, such a machine would be severely underutilized. Less expensive, lower throughput machines may be commercially available, or it may be possible to outsource metallization to third party vendors for a lesser fee.

Inspection - Relatively little is known regarding the nature, extent, or costs of inspection.

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Appendix A: Description of Technical Cost Modeling

Technical Cost Models (TCMs) are computer spreadsheets developed and applied by IBIS Associates for the simulation of manufacturing costs. TCMs are composed of two major sections: Inputs and Outputs. Inputs include material, geometry, and process specifications. The model outputs include Cost Summaries, which correspond to the unit operations of the process. In a Technical Cost Model, cost is assigned to each unit operation in a process flow diagram. Each unit operation represents one or several pieces of equipment operating at a common production rate. Together, this equipment makes up a station. Each station is characterized by factors including number of laborers, equipment and tooling investment, power consumption, and floor space requirement. Based on these factors as well as material cost, part geometry, and other specifications, TCMs account for product cost in the following categories.

- Variable Cost Elements
  - *Material Cost*
  - *Labor Cost*
  - *Utility (energy) Cost*
- Fixed Cost Elements
  - *Equipment Cost*
  - *Tooling Cost*
  - *Building Cost*
  - *Maintenance Cost*
  - *Overhead Labor Cost*
  - *Cost of Capital (interest payments)*

TCMs may be predictive or descriptive, and may model primary fabrication or secondary finishing operations. In predictive models, based on the specification of a particular product, the following values are predicted via regression analysis: cycle time or production rate, equipment and tooling investment, power consumption, and required floor space. In descriptive models, these values are input directly by the user.

Technical Cost Models can be used to accomplish tasks that include the following.

- Simulate the costs of manufacturing products
- Establish direct comparisons between material, process, and design alternatives
- Investigate the effect of changes in the manufacturing scenario on overall cost
- Identify limiting process steps and parameters
- Determine the merits of specific process and design improvements

A primary use of TCMs is in linking them to one another and to secondary analysis modules. IBIS has a library of over fifty models of primary and secondary operations in the areas of metals, ceramics, plastics, composites, and electronic materials. Multiple primary fabrication and secondary assembly process models can be linked together to model the complete production of a product. Technical Cost Modeling can be integrated with Activity Based Costing (ABC) for the simulation of direct and indirect costs for families of parts at the factory, division, or company level. They can also be linked with financial forms such as income statements, cash flow, and balance sheets for complete business analyses.

Technical Cost Modeling is implemented on a computer spreadsheet such as Lotus 1-2-3 or Microsoft Excel. The power and flexibility of using a computer spreadsheet facilitates rapid data storage, data manipulation, and output recalculation.

Appendix B: Interviews with CVD Diamond Authorities

F.M. Cerio, Crystallume

Mr. Cerio has published an article on assembling the apparatus for the CVD of diamond by the DC arc jet method. In talking to him about this article, he said the following:

- He did not think the polishing of the growing substrate was necessary for this method.
- If a substrate was polished, he thought this would only be beneficial if one wants to "pop off" the diamond film from the growing substrate after deposition is completed, or in mid deposition.
- If the final diamond film is to be more than 200 um thick, he thought that seeding would be a waste of time. This is because seeding will speed the nucleation rate of the diamond crystals, but a high nucleation rate is only a factor in the deposition time of diamond films thinner than 200 um.
- The surface quality of the underside of the diamond film is the same as the surface quality of the diamond g ,wing substrate, forming a "mirror image."
- The time to etch a silicon substrate took only a "few minutes." This was using the substrates from his article, ranging from 0.02 inch thick to 0.08 inch thick. The molybdenum took longer due to the formation of oxides on the surface, which slowed the reaction.
- This etching took place in a plastic tub (teflon surface) in a hood.

Grant Lu, Norton Diamond Films

Mr. Lu has written numerous articles on the DC arc jet method for CVD diamond, and has met with John Busch of IBIS to discuss the IBIS models. The following is a brief synopsis of discussions with Mr. Lu.

- Scratching or not scratching will not affect the deposition rate.
- Seeding or not seeding will not affect the deposition rate.
- For heat sink applications, the diamond film would be polished and metallized. He could not divulge the polishing times, but he said the metallization would amount to about 1 um and would be made of three metal layers: Titanium, Platinum, Gold.
- He also thought that if the diamond growing substrates were reused, these substrates would need to be polished before each use.

E. Pfender, University of Minnesota

Mr. Pfender has published many articles on the DC arc jet method for CVD diamond, and had the following thoughts:

- Hydrogen quality does not matter for tool applications, but should for electronic applications. Further, he stated that it would be important to recycle the hydrogen.
- Silicon needs to be scratched for higher nucleation rates, but molybdenum need not be scratched.
- The microwave method requires both polishing and scratching of the diamond growing substrate.
- For 5 to 10 micron diamond film polishing, the YAG laser would be useful.
- The best commercial method for polishing diamond in his opinion would be hot iron polishing, using chemicals and temperatures of 1000ÉC to dissolve the carbon.

Yonhua Tzeng, Auburn University

Mr. Tzeng held a conference at Auburn University attended by John Busch of IBIS, and offered the following comments:

- He thought that diamond polishing would require the removal of 50 to 100 um of diamond due to crystal growth.
- It is not necessary to repolish the reusable substrate.
- The diamond growing substrate should be a high temperature metal such as molybdenum or tungsten.
- Use a diamond sciafe, a disk of iron, to polish the diamond film.

Anne McKibbon, Crystallume

Anne McKibbon works for Laurie Conner and was very knowledgeable and helpful with information:

- Crystallume is mainly selling 300 um thick diamond films, with a few 500 um films as well, although "they are not cost effective." This is based on the assumption that one can get by with a 300 um diamond film. She also suggested that one does not have to use a pure diamond heat sink, but could probably use another material with diamond 1:1 in thickness.
- She has heard of diamond being used as the substrate for the circuit, and sometimes Crystallume does not know what their diamond film is being used for.
- The diamond is grown on silicon (about 1 mm thick), and after the deposition is complete, the silicon is etched off (etching process not known).
- Crystallume has the capability to polish one side of the diamond film. This would be the side exposed once the silicon substrate is etched off. The amount polished off is not known, but would depend on the application.
- The inspection of the diamond films is first a surface check for "holes and pits." The diamond film is sometimes put back in the deposition chamber to

rectify this problem. Also, there is a spectroscopy check for quality, but probably not a 100% inspection rate. Thermal conductivity quality checks are less frequent than the optical (spectroscopy) checks, and are usually performed by the customer.

- The metallization is usually 1000 Angstroms of titanium, the same thickness of platinum, then the same thickness of gold (being the contact metal with the chip mounted on top); adding up to 0.3 microns of metallization - "just enough to have a layer of metal." These are the same metals and sequence as with Grant Lu of Norton, who said it all was about 1 micron thick.

Dr. Don Smith, Astex

Astex has an interest in selling their microwave CVD diamond equipment, and therefore has an open policy about the details of their technology. Dr. Smith had the following comments:

- Astex uses silicon substrates and etches them off after deposition, but they are conducting research into reusable substrates. These would have to be polished before each use.
- Some of the required qualities of a reusable substrate could be poor diamond film adhesion, poor compatibility of coefficient of expansion with diamond, shape of substrate allowing substrate/diamond dissociation, or will be able to wet etch the intersection plane of the substrate/diamond materials using capillary action.
- Molybdenum would be suitable due to its conductive qualities - could use a 0.1 inch thick substrate instead of the current 0.25 inch thick silicon substrates.
- Astex uses gases 99.999% pure or better, but could imagine backing away from this purity for uses in heat sink and cutting tool applications.
- Astex does not use an inert gas in their process (microwave), but, due to current DC arc torch designs, he believes that the DC arc method must use an inert gas to prevent torch melting. An exception to this is the Diamant Boart company in Belgium (presented paper at Heidelberg).
- The microwave torch CVD diamond deposition machine that Astex sells recycles the exhaust gases (made up of H_2, CH_4, O_2, CO_2, C_2H_2, CO, H_2O, and "twenty others") by cooling (about $10K, 2kW of energy to absorb), filtering for particulate, compression, and reflowing to the reactor (the recirculation equipment costs about $200K of the $600K price for this apparatus). This recirculation is occurring at a rate of 1000 liters/min, and the gas cycles in fifteen minutes. One liter per minute of fresh gas concentration is flowing into the system, and the same volume rate is being disposed from the exhaust; this is to adjust for the carbon losses to the diamond film.

- The molar concentrations of C, H, and O are maintained during the deposition as indicated in an article by Peter Bachmann in Vol 1, No 1 of Diamond and Related Materials (1991).
- Westinghouse has recently purchased one of the $600K microwave torch CVD diamond deposition machines. It has a capacity of two eight inch diameter wafers, runs on five kW, deposits thirty mg per hour, and includes computer control and a warranty.
- Astex is working on a machine to deposit on a twelve inch diameter wafer, using microwave diffusion technology, at 75 kW, depositing 500 mg per hour. The current microwave diffusion reactor can deposit on two to three inch diameter wafers, at five kW, depositing 70 mg per hour. Astex has a goal of achieving 1 gram per hour diamond deposition.
- Astex does not polish the diamond film, this is subcontracted. Contact Evelio Sevillano at Astex.
- In comparing the costs of different company's systems, consider that the Astex machine price includes the actual equipment costs, the warranty (maintenance) costs, and costs for research and development.

Appendix C: Miscellaneous Interviews

Dave Walter, Texas Instruments (MCM Division)

Dave Walter is a process engineer in the MCM manufacturing operations at TI. He is quite knowledgeable of diamond films and offered the following:

- The diamond surface needed for use in the heat dissipation in MCMs is 20 micro inch RMS, and 0.5 mil per inch flatness.
- The metal plating on the diamond film is determined by the application. and would be from 1 to 3 microns thick.
- Said "[you've] got to have a hell of a thermal problem to use a diamond film in your application." This was referring to the costs of using diamond. Also said "for our application, we do not need to polish the surface"
- The reason for polishing is to make a uniform and maximum effectiveness heat sink. This is because the spaces between the peaks of the diamond film will not necessarily be filled in by metallization, leaving less surface area of the diamond heat sink in contact with the metal.

Professor Szekely, MIT Materials Science Dept.

Professor Szekely is knowledgeable on the subject of CVD and thermal properties of materials and thought that the polishing of diamond films would be due to macro- as opposed to micro- surface geometries.

Wayne Koch, Airco

Wayne Koch supplies gases to Norton Diamond Films. He said that the purity they use is "five nines," or 99.999% pure. This applies to the hydrogen and argon.